

BUILDING AND BRIDGE POUNDING DAMAGE OBSERVED IN THE 2011 CHRISTCHURCH EARTHQUAKE

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SUMMARY

This paper describes pounding damage sustained by buildings and bridges in the February 2011 Christchurch earthquake. Approximately 6% of buildings in Christchurch CBD were observed to have suffered some form of serious pounding damage. Almost all of this pounding damage occurred in masonry buildings, further highlighting their vulnerability to this phenomenon. Modern buildings were found to be vulnerable to pounding damage where overly stiff and strong ‘flashing’ components were installed in existing building separations. Soil variability is identified as a key aspect that amplifies the relative movement of buildings, and hence increases the likelihood of pounding damage. Pounding damage in bridges was found to be relatively minor and infrequent in the Christchurch earthquake.

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Figure 1: Examples of URM pounding damage. Left: minor damage. Right: major damage partially caused by pounding

INTRODUCTION

While pounding damage is generally accepted to occur during earthquakes, systematic investigation of this type of damage after a major earthquake has been rarely reported in literature [1-3]. Following the 22nd of February 2011 Christchurch earthquake, two surveys were performed specifically documenting pounding damage. The first survey consisted of a building by building external inspection throughout the Central Business District (CBD) three weeks after the earthquake. The extent of this survey was roughly bordered by Oxford Tce, Armagh St, Madras St and Tuam St; however the internal streets of the central exclusion zone (bordered by Colombo St, Hereford St, Madras St and Lichfield St) were not surveyed due to safety concerns. This survey was performed in a similar, but more thorough, manner to the pounding survey performed after the September 2010 Darfield earthquake [3]. The second survey was not restricted by area; however the extent of this survey was limited by the amount of time available to the authors immediately following the earthquake. Examples of notable pounding damage in either bridge or building structures were documented when observed.

This paper is structured in three parts. Pertinent features of the CBD survey are presented in a similar format to the paper detailing the pounding damage after the 2010 Darfield earthquake [3] to allow direct comparison. The effects of subsoil on pounding damage are then discussed and illustrated using damage observed outside the CBD. Finally, the observed bridge pounding damage is presented.

It is also noted here that the results of the CBD building survey have been described and analysed in more detail elsewhere [4]. Readers interested in the details of the survey and its results are recommended to read this reference [4].

Pounding describes the collision of adjacent structures due to the structures' relative movement exceeding their initial separation. Pounding is usually associated with large relative velocities causing a massive and sudden force at the point of impact. However, it may be argued that many buildings without initial separation did not actually 'pound' in the Christchurch earthquake. This is because it is likely that these buildings were in constant contact throughout the earthquake, so a relative velocity between the two buildings never occurred. In such circumstances, the term 'building interaction' more appropriately describes this behaviour. This paper does not make a distinction between pounding and building interaction, since both can have detrimental effects and cause load transfer between the affected buildings.

Since these surveys were limited to external damage, no account of pounding damage between seismic joints, or collisions between structural elements of the same building

have been made. However, it is acknowledged that these effects did occur in both the Darfield and Christchurch earthquakes.

OBSERVATIONS OF BUILDING POUNDING DAMAGE

Building pounding damage was observed in a small fraction of the overall CBD building stock. Most buildings surveyed within the CBD were observed to have effectively no building separation, meaning almost all surveyed buildings could interact with neighbouring buildings. In total, 6% of the 376 CBD buildings surveyed suffered significant damage that could be confidently attributed to pounding, while two building collapses were tentatively partially attributed to pounding damage [4]. 22% of surveyed buildings were observed to have some evidence of damage due to pounding. The vast majority of significant pounding damage was observed in unreinforced masonry (URM) buildings. The severity of this pounding damage also greatly varied from localised glazing damage to building collapse.

It is considered that the high frequency and severity of the observed pounding damage primarily due to the lack of separation between adjacent buildings in Christchurch CBD. The absence of separation is common between older buildings and has been frequently observed in many other New Zealand cities, including Wellington and Dunedin; thereby making them prone to severe pounding damage in a strong earthquake.

Pounding damage to URM buildings (for example, Figure 1) occurred sufficiently frequently to enable identification of common damage patterns (Figure 2). Masonry cracking typically extended from the topmost point of contact between two buildings to the nearest window arch or lintel in each building. Cracking frequently extended further from the window opening through to the top of the building's parapet, although this parapet damage was not usually attributed to pounding. Multistorey buildings occasionally also presented damage at lower floors, although this damage was observed to be progressively less severe as the distance from the topmost point of contact increased. Cracking was also observed to concentrate in stiff lateral elements, such as wall sections with wide spacings between window penetrations (Figure 2a). Occasionally, local crushing of masonry units was observed at the point where two floors collided. When buildings of differing height collided, the floor immediately above the topmost point of contact also frequently suffered notable cracking. Figure 2b presents an idealised load path diagram, which also reflects the typically observed masonry damage distribution. In reality the damage 'struts' were not oriented at 45 degrees. This angle was instead governed by the building's wall penetrations.

Modern buildings generally suffered less pounding damage. This is attributed to the greater building separations adopted in newer buildings and the presence of weaker adjacent buildings (for example, if a concrete reinforced frame building collided with a URM building, damage is more likely to occur first in the URM building due to its weak, brittle properties). The primary source of pounding damage in modern buildings with separation was instead observed where building separations were infilled with cosmetic flashings (Figure 3). While flashings are intended to cover the gap between adjacent buildings, the detailing of some flashings created stiff and strong elements, which transferred significant force between the two buildings. In some instances the flashings caused failure of adjacent building elements, while in other instances the entire flashing detached from both buildings. Flashing detachment can cause a sizable amount of falling debris when the buildings have multiple storeys. Furthermore, this form of damage can be simply avoided by designing flashings to compress/crush and ensuring they are adequately anchored to one building only. Five instances of significant damage resulting from force transfer through building flashings were observed within the CBD.

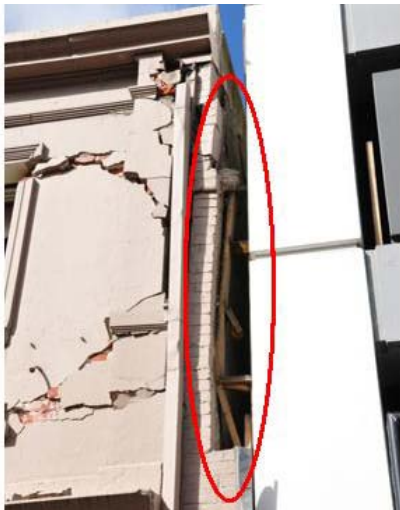


Figure 3: Building damage caused by framed flashing

Three instances of buildings apparently being crushed from either side by adjacent buildings were also observed (Figure 4). This was evidenced by façade collapse and localised crushing damage at the points of contact with adjacent

buildings. It is noted that some engineers have expressed some doubt to the first author that the adjacent buildings contributed to this failure. However, an alternative explanation for the observed damage at the contact points has thus far not been presented. If pounding did contribute to these collapses, it is a particularly dangerous consequence for any pedestrians in the vicinity when an earthquake occurs, in addition to potentially compromising the building's overall stability. The illustrated example's façade was constructed of reinforced concrete, which typically performed very well elsewhere in the CBD. This further highlights the potential danger of this type of damage.



Figure 4: Facade loss attributed to building crushing

Collisions where one building's façade is set back from the adjacent building's façade amplified the damage at these locations. This damage was also reported in the Darfield pounding observations [3]. Buildings that suffered setback damage in the Darfield earthquake were further damaged in the Christchurch earthquake, however none were observed to cause any catastrophic failures.

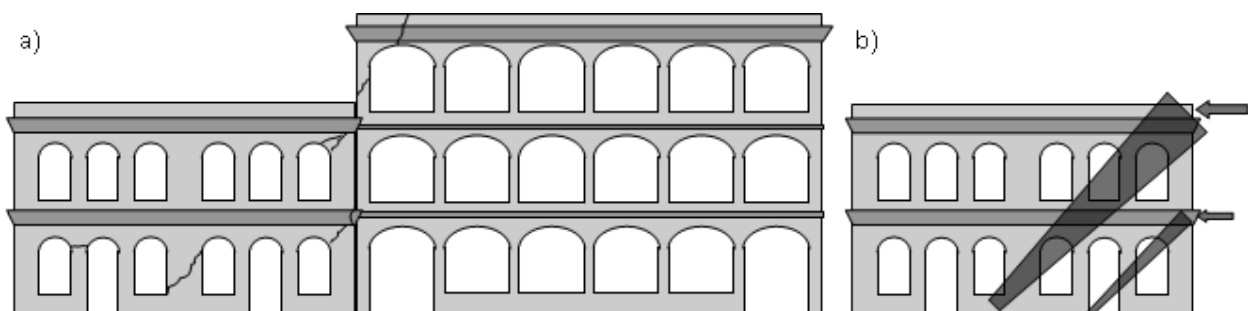


Figure 2: Damage to URM buildings. a) Typical pounding damage. b) Idealized masonry strut damage. Arrows denote floor collision points of the adjacent building. Width of the shaded zone indicates approximate severity of damage. Figure reproduced from [4].



Figure 5: Pounding damage caused by buildings with greatly differing heights. Note image is distorted due to panoramic photography

EXCEPTIONAL EXAMPLES OF POUNDING DAMAGE

As was also observed in the Darfield earthquake, very little pounding damage was observed between buildings of greatly differing overall heights. This is again primarily attributed to the greater separations that generally surround taller buildings. However, Figure 5 presents one building configuration where extensive pounding damage did occur. Pounding between the central building and the taller rightmost building also occurred in the Darfield earthquake. The damage in the Darfield earthquake was minor, although it was noted that this damage occurred in the vertical elements of the primary gravity structure [3].

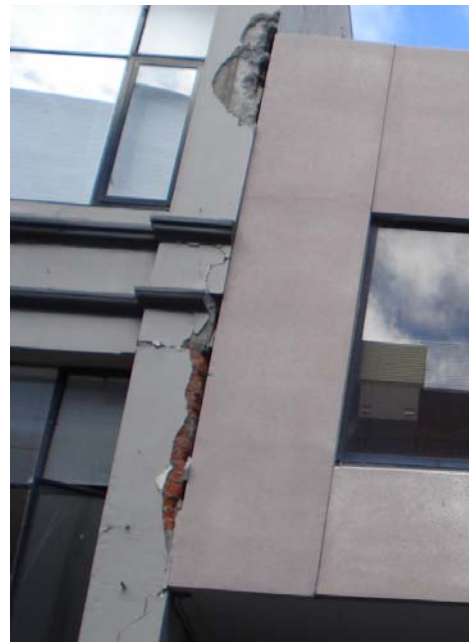


Figure 6: Damage between central and rightmost building

The Christchurch earthquake significantly increased the damage in the central building, and also caused damage at the boundary with the leftmost building. At the right interface of the central building the observed damage is predominantly spalling (Figure 6), although cracking also extended below the contact interface. The damage at the left interface is more severe. The masonry column of the central building has been offset approximately 30 mm due to collision with the left building. It is considered that the central building was crushed by the surrounding buildings, primarily due to the greatly differing earthquake response of the taller rightmost building.



Figure 7: Pounding between 1 storey and 4 storey buildings. Damage to four storey building not attributed to pounding

The range of buildings affected by pounding sometimes extended to buildings where pounding would not normally be anticipated. One single storey building was observed to suffer substantial pounding damage as a result of contact with a neighbouring four storey building (Figure 7). The neighbouring four storey building was substantially damaged during the Christchurch earthquake, however this damage is not attributed to pounding. As a result of this damage, the lateral stiffness of the neighbouring building reduced, causing greater building deflection. It is considered that this effect has increased building damage, although its significance is unknown. Approximately 10 mm building separation was observed between these buildings.

Two building collapses within the CBD are partially attributed to pounding. Both these cases involve URM buildings that were constructed circa 1900. Figure 8 illustrates the damage caused to a two storey URM building that sustained pounding during the Christchurch earthquake (shown on the left). Significant damage has also been sustained by the adjacent right building. These buildings were externally surveyed after the Darfield earthquake and were found to be separated by approximately 50 mm at ground level, but were in contact at roof level. It was concluded that the two storey building had begun to lean, although whether this was due to the Darfield earthquake could not be determined. As these buildings were in contact, pounding undoubtedly occurred during the Christchurch earthquake. However, the primary cause of collapse is attributed to the URM construction. Whether pounding appreciably contributed to this collapse is very difficult to determine, due to the level of destruction that has occurred.



Figure 9: Masonry damage after the Darfield earthquake

The second building configuration suffering collapse was also documented after the Darfield earthquake, as shown in Figure 9 (see also Figure 2 in [3]). Figure 10 displays the damage following the Christchurch earthquake. Figure 9 is located at the first floor between the left and central buildings, and is quite possibly the initiation point of the global collapse.



Figure 8: Two storey building collapse involving pounding. Primary cause of collapse is attributed to URM construction



Figure 10: Building collapse involving building pounding. Primary cause of collapse is attributed to URM construction.
Photo courtesy of Colin Monteath, Hedgehog House.

The damage shown in Figure 10 indicates that the central and leftmost buildings were likely to be constructed with a shared party wall. This can be observed where wall sections remain standing at the building interface. At the second level, a 100 mm thick brick wall appears to have supported both buildings. This evidence is also supported by the interior finishings that can be observed on the 'exterior' of this wall. Nevertheless, localised damage consistent with pounding is present between the central and rightmost buildings. Once again it is difficult to discern the level of influence pounding has had on the presented collapse. The primary cause of collapse is attributed to the URM construction. However, it is credible that the severity of this damage would have been greatly reduced if adjacent buildings had not been present.

EFFECT OF SUBSOIL ON POUNDING DAMAGE

One of the main causes of relative building responses is the difference in the dynamic properties of the adjacent structures. An assumption of spatially uniform ground motions can be justified when the structures are very close to each other, e.g. neighbouring buildings. However, even if all participating structures experience the same ground excitation relative responses will occur owing to their different dynamic properties.

The condition of supporting soil is normally non-uniform. In earthquakes the dynamic soil stiffness is complex. To describe the influence of subsoil on the dynamic properties of the

whole soil-foundation-structure system, for simplicity it can be assumed that the soil stiffness is constant, the footing is rigid and the influence of the vertical soil stiffness is negligible. It should be noted that in reality the soil stiffness depends on the vibration frequencies of the footing (see e.g. [5]), and the stiffness can also be nonlinear due to plastic deformation of soil, e.g. in the case of soil liquefaction. The influence of the subsoil on the fundamental period of the soil-foundation-structure system can be estimated from the following equation.

$$\tilde{T}_i = T_i \sqrt{1 + \frac{k_i}{k_{ix}} \left(1 + \frac{k_{ix} h_i^2}{k_{i\phi}} \right)} \quad (1)$$

where \tilde{T}_i and T_i are the fundamental period of the i^{th} structure with subsoil and with an assumed fixed base, respectively;

k_i , k_{ix} and $k_{i\phi}$ are the bending stiffness of the i^{th} structure, the static soil stiffness for horizontal and rocking movements of an assumed rigid footing of the i^{th} structure, respectively;

h_i is the effective height of the i^{th} structure;

$i = 1 \dots n$, and n is the total number of the participating structures.

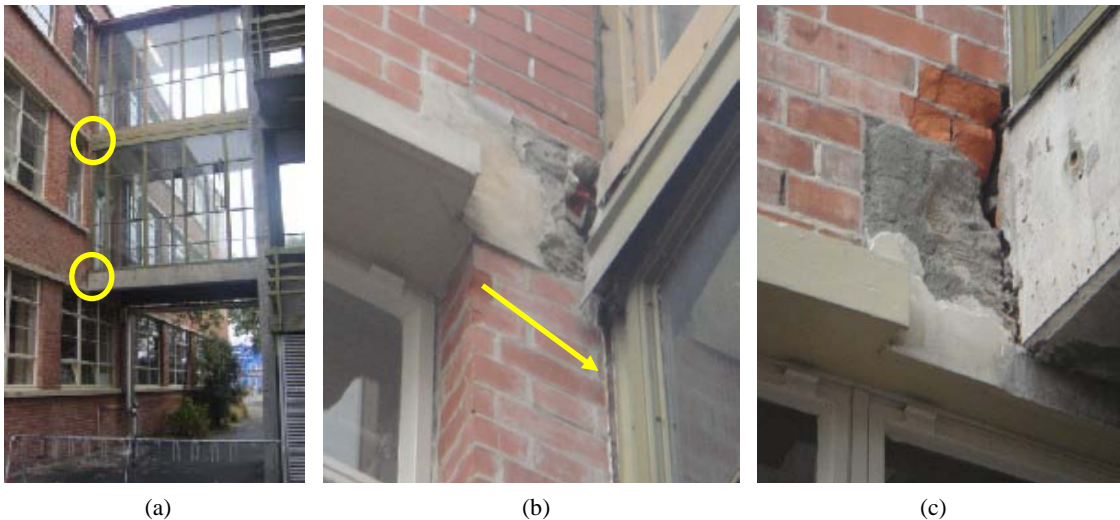


Figure 11: Pounding damage to buildings at the Christchurch Polytechnic Institute of Technology. (a) Adjacent buildings with pedestrian bridges, (b) upper and (c) lower pounding locations.

Equation 1 shows that the fundamental period of the whole system is determined by the ratio of the structural bending stiffness to the horizontal soil stiffness, the rotational soil stiffness and the effective height of the structure. In the case of long extended structures, e.g. long bridges, non-uniform site conditions and thus unequal system periods are to be expected also for adjacent structures with the same fixed-base fundamental period.

Even if the foundation of two adjacent structures is the same, i.e. $k_{1x} = k_{2x}$ and $k_{1\phi} = k_{2\phi}$, and the fixed-base fundamental periods of the structures are equal, i.e. $T_1 = T_2$, the adjacent structures will still have different fundamental periods $\tilde{T}_1 \neq \tilde{T}_2$ if they have unequal effective heights $h_1 \neq h_2$. Consequently, the two structures will respond differently to the same ground excitation and relative responses will occur.

Pounding between adjacent buildings can be avoided if a sufficient gap exists. In some cases, however, although the adjacent buildings are well separated, pounding can still take place. This is the case when the buildings are linked by pedestrian bridges as the buildings at the Christchurch Polytechnic Institute of Technology along the Madras Street in Figure 11(a) show. The upper and lower pounding locations are indicated by the circles. The damage due pounding of the upper floor of the pedestrian bridge is displayed in Figure 11(b). The residual opening relative movement can also be clearly seen indicated by the arrow. Figure 11(c) shows the damage to the unreinforced masonry wall due to pounding of the lower RC floor of the pedestrian bridge. In the case considered both adjacent buildings have different fundamental periods owing to their dissimilar building configuration, and thus different oscillation pattern are to be expected. Previous studies on pounding responses between buildings linked by pedestrian bridges in near-source earthquakes have shown that neglecting of soil-foundation-structure interaction can underestimate pounding potential and also the induced vibrations in the buildings [6].

COMPARISON WITH PREVIOUSLY IDENTIFIED BUILDING POUNDING HAZARDS

Previously, six building characteristics had been identified that increase the likelihood of pounding damage [7]. A brief comment is made on each of these characteristics below.

1. **Floor-to-column or floor-to-wall pounding.** Approximately one third of the observed pounding damage occurred between adjacent buildings with differing floor heights. This type of building configuration causes collisions between each building's floors and their neighbouring building's columns or walls. This form of collision is observed to cause more severe localised damage in vertical elements (see Figure 5 and Figure 6).
2. **Adjacent buildings with greatly differing mass.** Adjacent buildings with greatly differing mass were observed to have suffered pounding damage. However, this damage was not observed to be noticeably different to that of other pounding configurations.
3. **Buildings with significantly differing total heights.** Greatly differing overall building height was observed to amplify damage when contact occurred. However, it was also generally observed that buildings with this configuration usually also presented with greater building separations, which significantly mitigates this hazard.

4. **Similar buildings in a row with no separation.** Unlike the Darfield earthquake, evidences of damage due to interactions of more than two buildings were relatively common in the Christchurch earthquake (for example, Figure 4, Figure 5 and Figure 10). This type of damage was noted primarily between buildings with significantly different dynamic properties. Damage between similar buildings was less common, but was occasionally observed in the survey. Previous studies have identified similar buildings in a row as being susceptible to pounding damage [8]. In particular, the buildings at either end of the row are vulnerable to additional damage due to momentum transfer from the central buildings. In this survey, however, no obvious amplification of end building pounding damage was observed.
5. **Building subject to torsional actions arising from pounding.** Torsional pounding interaction was found to be particularly difficult to identify from external inspection. Only one possible case of torsional pounding interaction was observed in the CBD (Figure 14).
6. **Buildings made of brittle materials.** As was also observed in the Darfield earthquake, URM was found to be the defining characteristic of pounding damage in this earthquake. Approximately 3/4 of pounding damage was observed to involve URM buildings. All moderate to large pounding damage was found in URM buildings.



Figure 12 Possible torsional building pounding due to irregular plan layout



Figure 13: Fitzgerald Avenue Bridge. Pounding damage (a) at the abutment, (b) to the immediate adjacent girder and (c) to the other abutment.

POUNDING BETWEEN BRIDGE STRUCTURES

Although the Christchurch earthquake did not cause spectacular damage to bridge structures due to their relative movement, i.e. bridge collapses due to pounding and unseating of the bridge deck such as observed in the 1995 Kobe earthquake in Japan [9], the 1999 Chi-Chi earthquake in Taiwan [10] or the 2010 Maule earthquake in Chile [11], the very short but strong pulses still caused pounding damage to a number of bridge structures in Christchurch and surroundings. Figure 13(a) shows the pounding damage to the abutment of the Fitzgerald Avenue Bridge. The damage to the immediate adjacent girder can be seen in Figure 13(b). The pounding caused a spall of the edge of the girder. Damage to the other abutment in Figure 13(c) occurred even along the entire height of the abutment wall as indicated by the circles. The cracks of the wall are indicated by the dotted lines. It should be noted that lateral spreading of the ground surface due to soil liquefaction occurred in the surroundings. This spatial variation of the ground movements might have amplified the relative movement between the two bridge structures and contributed to the poundings.

In Figure 14 the significant damage to the Ferrymead Bridge can be observed. The bridge is very valuable since each day approximately 30,000 vehicles were using the bridge that links Christchurch and Lyttelton. Severe soil liquefaction has been observed in the area, and thus behaviour similar to the Fitzgerald Avenue Bridge was expected. Figure 14(a) shows pounding induced spalling at the edge of the girder of the Ferrymead Bridge, which is similar to that observed at Fitzgerald Avenue Bridge (Figure 13(a)). The effect of the unequal soil settlement might also have amplified the closing relative movement as one can observe in Figure 14(b). The damage due to pounding to the upper deck is indicated by the circle. The closing relative movement caused a large horizontal crack at the interface between the upper deck and the supporting abutment as indicated by the arrow. Direct damage at the pounding location can be seen in Figure 14(c) (marked by a circle). The horizontal crack in the abutment due to the pounding is indicated by the arrow.

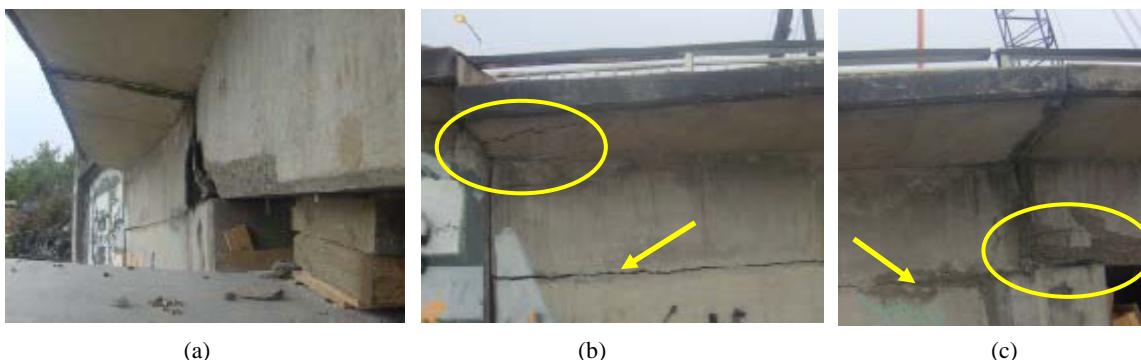


Figure 14: Ferrymead Bridge. Pounding damage (a) to girder, (b) at abutment and (c) at girder-abutment location.

CONCLUSIONS

The following conclusions are drawn from the observations discussed in this paper:

- Pounding damage observed within Christchurch CBD ranged from cosmetic to partial and possibly complete building collapse. Evidence of interactions between adjacent buildings occurred in 22% of the surveyed CBD buildings. However, significant building pounding damage occurred in only 6% of the surveyed buildings.
- Modern buildings were primarily endangered by pounding when flashings between buildings were constructed with stiff and strong materials that allowed force transfer across building separations. This hazard can be mitigated by using compressible flashings attached to one building (but not both).
- Severe pounding damage was observed to occur almost exclusively in URM buildings. This is primarily attributed to URM's brittle response to any high magnitude force.
- While very rare, building pounding damage can occur in buildings as small as one storey.
- It is likely that the closing relative movement between adjacent structures is amplified by the spatially unequal ground movements due to the liquefaction at local site.
- The influence of nonlinear soil behaviour on the dynamic behaviour of the adjacent structures and consequently on their pounding potential needs to be investigated.
- In the Christchurch earthquake only relatively minor pounding damage to bridges has been observed.
- Pounding damage remains a concern for future

earthquake events. Wellington is particularly hazardous since it is close to several major faults and hosts many URM buildings with little or no inter-building separation.

chile/wp-content/uploads/2010/04/Yashinsky-et-al-Bridges.pdf.

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REFERENCES

1. Bertero, V.V. *OBSERVATIONS ON STRUCTURAL POUNDING*. in *The Mexico Earthquakes—1985: Factors Involved and Lessons Learned*. 1986. Mexico City, Mexico: ASCE, New York, NY, USA.
2. Kasai, K. and B.F. Maison, *Building pounding damage during the 1989 Loma Prieta earthquake*. *Engineering Structures*, 1997. **19**(3): p. 195-207.
3. Cole, G.L., et al., *Interbuilding pounding damage observed in the 2010 Darfield earthquake*. *Bulletin of the New Zealand Society for Earthquake Engineering*, 2010. **43**(4): p. 382 - 386.
4. Cole, G.L., R.P. Dhakal, and F.M. Turner, *Building pounding damage observed in the 2011 Christchurch earthquake*. *Earthquake Engineering & Structural Dynamics*, 2011: p. n/a-n/a.
5. Sieffert, J.-G. and F. Cevaer, *Handbook of impedance functions*. 1992, Nantes, France: Quest Editions, Presses Academiques.
6. Chouw, N., *Influence of soil-structure interaction on pounding response of adjacent buildings due to near-source earthquakes*. *Japanese Society of Civil Engineers Journal of Applied Mechanics*, 2002. **5**: p. 543 - 553.
7. Cole, G.L., et al., *Building pounding state of the art: Identifying structures vulnerable to pounding damage*, in *New Zealand Society for Earthquake Engineering Annual Conference (NZSEE 2010)*. 2010: Wellington, New Zealand. p. P11.
8. Jeng, V. and W.L. Tzeng, *Assessment of seismic pounding hazard for Taipei City*. *Engineering Structures*, 2000. **22**(5): p. 459-471.
9. Chouw, N., *Effect of the earthquake on 17th of January 1995 on Kobe*, in *Proceedings of the D-A-CH meeting of the German, Austrian and Swiss Society for Earthquake Engineering and Structural Dynamics*. 1995: University of Graz, Austria. p. p. 135-169.
10. Hamada, M., et al., *The 1999 Ji-Ji earthquake, Taiwan - Investigation into damage to Civil Engineering structures*. *Japan Society of Civil Engineers*, 1999: p. 176.
11. Yashinsky, M., et al. *Performance of highway and railway structures during the February 27, 2010 Maule Chile earthquake, EERI/PEER/FHWA bridge team report*. 2010 [cited 12/09/2011; Available from: <http://www.eqclearinghouse.org/20100227->